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Development of a Strategy Tool for Environmental Compliance Management

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Abstract

The EU environmental legislation restricts the use of certain substances in products and, in addition, sets targets for recovery of products reaching end-of-life (EOL). Little support is provided to producers on how to obtain the best design alternative for their products (meaning the best compromise between cost and environmental compliance). The authors propose a strategy tool based on the Analytic Hierarchy Process (AHP) as a solution to this problem. It will generate information needed to make the decision, will present it in a structured way and will permit the direct involvement of the users.

Keywords

Design for Environment (DFE), Cost Model, Strategy Tool, Analytic Hierarchy Process (AHP)

Introduction

With the increasing pressure of environmental legislation [1,2,3], the selection of the design and the manufacturing processes which comply with environmental requirements have become evermore complicated and onerous on OEMs (Original Equipment Manufacturers) as well as other players in the supply chain. In electronic or automotive engineering, for example, the goal of the designer is to determine the most cost effective design alternative in order to optimise the environmental compliance of the product, according to the requirements of the WEEE Directive, the ELV Directive and other related environmental legislation [1,2].

The design and evaluation of products against the criteria demanded by environmental legislation and the cost targets of the company has become an important challenge for companies all over the world [4,5]. Whilst trade-offs should include parameters such as quality, reliability, environment compliance and cost [6], it is not possible to suggest a precise algorithm to cater to because the solution depends on various factors such as the type of product, legislation or the company policy at that point in time.

The aim of this paper is to propose a decision-support model that can assist product designers in the decision-making process. The proposed model is based on information offered by the DFE Workbench tool presented in section 2, which uses Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. Section 3 proposes a strategy module to support designers in assessing the environmental performance of their products and their compliance with environmental legislation, as well as their effectiveness and viability such that a balanced trade-off can be made between cost and environmental compliance, leading to affordability and sustainability over the product life cycle.

Design for Environment – The DFE Workbench

The development of environmentally superior products (ESPs) represents the most recent obligation placed on designers [7,8].

In order to design ESPs, the authors developed the DFE Workbench (methodology and tool) which is focused on the analysis, synthesis, evaluation and improvement of the life cycle design of the product.

The DFE Workbench is a CAD integrated software consisting of 3 modules: the DFE module which is strictly related to design for environment, the cost module and the strategy module.

The DFE Module

The DFE module is a design for environment software tool integrated into a CAD environment (the application has been ported to Pro Engineer 2001, Solid Works 2000 and Catia V5 R16). It has been developed to assist and advise the designer in the development of ESPs in order to meet the requirements of the latest legislation related to environment and the customers' needs.

The DFE module consists of (see figure 1): the Impact Assessment System (IAS), the Structure Assessment Method (SAM), the Advisor Agent, the Knowledge Agent and the Report Generator.

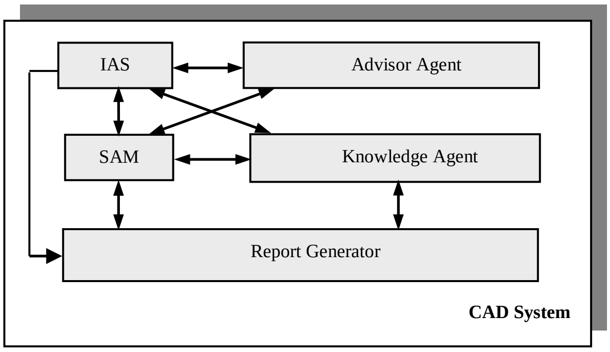

Fig. 1. The DFE module [7,8]

The *Impact Assessment System (IAS)* is an abridged quantitative approach to LCA, performing synthesis, evaluation, prioritisation and improvement of environmental data. It automatically extracts the appropriate data from the CAD drawing. Based on this information and the processes associated with each component, environmental impact may be calculated for each component or for the entire assembly.

The *Structure Assessment Method (SAM)* is a complex methodology, which quantitatively measures and records data such as material compatibility/substitution (taking into account fasteners), components' serviceability, number and types of fasteners, number and types of tools required for disassembly and total standard disassembly times and component removal times.

The *Advisor Agent* has two functions: firstly to prioritise variables generated by the IAS and SAM tools; secondly to give advice to the designer on alternative structural characteristics in order to enhance either the environmental impact or structural characteristics of the emergent design.

The *Knowledge Agent* provides advice to the designer in a consultative mode (for example, help to find a material with specific mechanical and environmental properties).

The *Report Generator* automatically generates reports on the product designed by the user.

Using the DFE module, several design alternatives can be generated according to the designer's choice or the suggestions made by the tool's advisor in order to improve the environmental characteristics of the product. IAS and SAM will calculate all indicators for each alternative. Design parameters that can be changed and that influence the product's impact on the environment as well as on costs include: type of material, mass, dimensions, no. of fasteners. Any change to these parameters can result in different processes which will result in a modification of the environmental impact and the total cost of the product.

The Cost Module

The Cost module models various costs associated with the product life cycle (see figure 2). It offers the designer a support tool that gives indications of the product's cost and also permits comparisons of design alternatives at the early stages of the design.

The cost model is a combination of life cycle costing (LCC), feature-based costing and activity-based costing (ABC). It aims to give the designer a complete picture of the product cost and to show the influence of different changes in the design on the total cost of the product. To effectively compare alternatives, the designer must be able to accurately estimate costs for the complete system so that 'what if' scenarios can be built.

The output of the Cost module is intended to give the designer a summary of the costs of the entire product life cycle: production cost, use cost, end of life (EOL) cost and environmental cost, all of which will be used by the Strategy module.

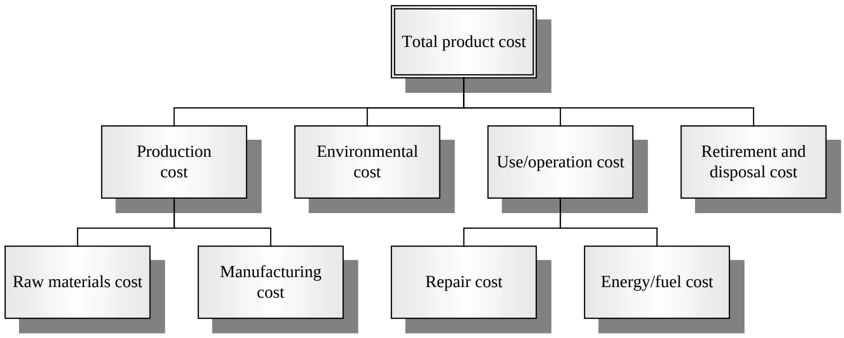

Fig. 2. Cost breakdown structure

Production cost

The production cost of the product is calculated using the ABC method [9]. The methodology is extended by using feature-based cost estimation in coordination with ABC (consumption of cost centres depends on the design parameters). This allows the designer to evaluate the product cost based on physical properties very early during the product design stage.

Environmental Cost

The model takes into consideration only the internal environmental costs related to the product which represent environmental costs that have a direct financial impact on the company (such as waste and emissions treatment cost, labelling cost, licence and permit fees).

Use/operation Cost

The costs categories considered in the cost model for the use/operation phase are repair/maintenance cost and energy/fuel cost. Design parameters such as Mean Time to Failure (MTTF) for unrepairable components and Mean Time Between Failures (MTBF) for repairable components are considered in the repair cost model. Depending on the type of product (energy consuming or fuel consuming), the energy cost or fuel cost is modelled for the entire product lifetime.

EOL Cost

An EOL option is defined for each component of the product and costs associated to that particular option are modelled.

The Strategy Module

The consideration of environmental criteria in the product design process can often lead to conflicts when it comes to the economical evaluation of the product design [6]. Consequently, it is important that compromises be found between environmental criteria and economic criteria. Such compromises can only be found by considering the need to respect the environmental objectives of the company, national and/or international environmental policies and legislation [1,2,10], in addition to economic constraints (costs).

The Strategy module addresses this compromise situation. It uses the Analytic Hierarchy Process (AHP) [11,12,13] for multi-criteria decision-making in the selection of a design alternative. The decision situation involves the consideration of variables which can be easily quantified into monetary units, as well as those environmental aspects which cannot. Therefore the decision-making process can be influenced by multiple criteria analysis and evaluation.

The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed as a methodology for multi-criteria modelling and decision-making [11,12]. It provides a framework for facilitating a systematic approach to decision analysis that can integrate and incorporate the values of the decision-makers and legislative constraints with technical information in order to examine the overall implications of each alternative [14].

AHP provides a hierarchical framework within which multi-attribute decision problems can be structured [11]. AHP is not a substitute for decision-making; it makes complex decision processes more rational by synthesising all of the available information about the decision in a system-wide and systematic manner and helps the designer prioritise the criteria in a manner that otherwise might not be possible [15].

The Strategy Module for Support of Decision-Making at the Design Stage

The challenge to the authors was to construct a strategy tool which included all relevant environmental and economic criteria and which could be applied to decision-making at the product's design stage. The goal was then to choose the design alternative which satisfied best all of the environmental and economic criteria. The AHP methodology was chosen for this purpose. Figure 3 shows the decision tree used by AHP to solve the design alternative selection problem.

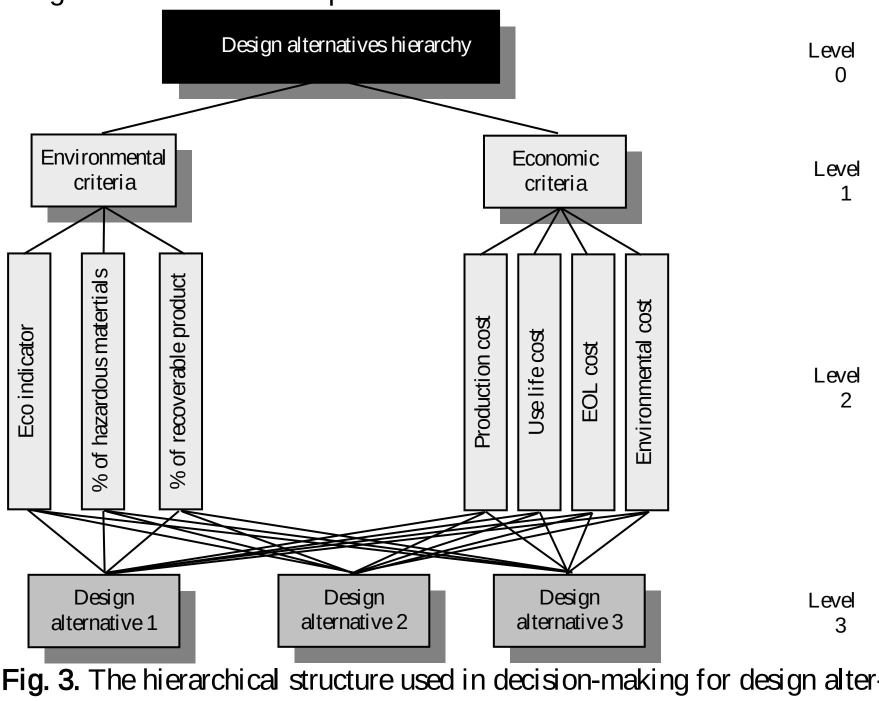

Fig. 3. The hierarchical structure used in decision-making for design alternatives

Once the hierarchical structure is defined, *pairwise comparison judgements* are made. An important feature of the tool is that it permits the direct involvement of the designer, which is very important considering that companies differ in the criteria they consider important according to the type of business and ownership of their product (e.g. leasing) and the product's life cycle (see figure 4).

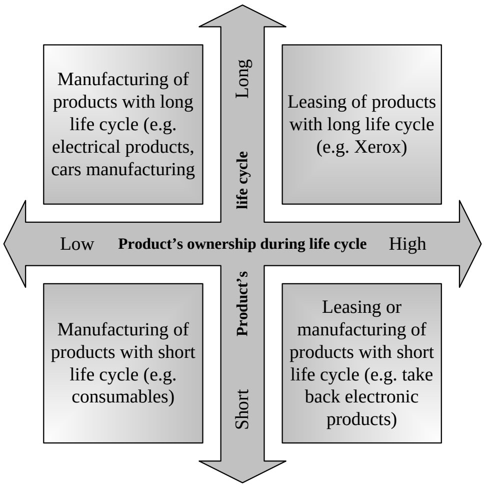

Fig. 4. Company types based on product's life cycle and ownership

The decision-maker (i.e. the user of the tool) compares each criterion to those that have the same parent node. According to the position of the company in the diagram in figure 4, indicators in the hierarchical structure (environmental and economic) will have different importance for the decision-maker.

Pairwise comparison matrices are then formed. Table 1 shows a matrix of pairwise comparisons of the criteria at level 1 in the decision tree with respect to the overall objective, i.e. obtaining the best design alternative. Criteria in rows (i) are scored against criteria in columns (j).

Table 1. Example of matrix of pairwise comparisons of the criteria at the first level in the decision tree with respect to the overall objective

i \ j	Environmental criteria	Economic criteria
Environmental criteria	1	7
Economic criteria	1/7	1

The diagonal values of any pairwise comparisons matrix are always 1 as each criterion is compared with itself. The lower triangular part of the matrix contains the reciprocal of the values in the upper triangular part ($a_{ji}=1/a_{ij}$).

The next step is obtaining the *relative importances of criteria and alternatives* using the eigenvector method. Let us denote the pairwise comparisons matrix as $A=(a_{ij})$. If n criteria (C_1, C_2, …, C_n) at the same level are compared, then the relative weights are the normalised elements of the eigenvector $w=(w_1, w_2, \ldots, w_n)$ which verifies the equation:

$$(\lambda_{max} I - A)\, w = 0 \tag{1}$$

where λ_{max} is the largest eigenvalue of A

In practice, to determine the relative weights the sum of each column will be made. Then each number in the matrix will be divided by the sum of the column in which it appears. By averaging across each row, the final relative weight is obtained for each criterion.

Let us denote the relative weights derived from pairwise comparisons of the criteria at level 1 as:

$$w_i, \text{ where } \sum_{i=1}^{2} w_i = 1 \tag{2}$$

and i = 1, 2; i = criterion at level 1

The relative weights derived from pairwise comparisons of the criteria at level 2 corresponding to each criterion at level 1 are:

$$v_{ij}, \text{ where } \sum_{j=1}^{n} v_{ij} = 1,\ \forall\, i,\ i = 1, 2 \tag{3}$$

and

i = criterion at level 1

j = 1, 2, …, n

j = criterion at level 2 corresponding to criterion i at level 1

n = number of criteria at level 2 corresponding to criterion i at level 1

The relative weights derived from pairwise comparisons of the alternatives at the bottom level with respect to each criterion at level 2 are:

$$V_{kl}, \text{ where } \sum_{l=1}^{3} V_{kl} = 1,\ \forall\, k,\ k = 1, 2, \ldots, m \tag{4}$$

and

l = 1, 2, 3; l = alternative

k = criterion at level 2

m = total number of criteria at level 2

Once all the eigenvectors have been obtained, the *process of synthesis* can proceed. The absolute importances of criteria at level 2 corresponding to each criterion at level 1 will be obtained with the formula:

$$U_{ij} = w_i v_{ij}, \ \forall\ i, i = 1, 2; \ \forall\ j, j = 1, 2, \ldots, n \tag{5}$$

where
i = criterion at level 1
j = criterion at level 2
n = number of criteria at level 2 corresponding to criterion i at level 1

Let us denote the absolute importances of criteria at level 2 calculated before as:

$$W_k \tag{6}$$

where
k = 1, 2, …, 7
k = criterion at level 2

Then the scores of the alternatives (design alternatives) are:

$$S_l = \sum_{k=1}^{7} V_{kl} W_k, \ \forall\ l, l = 1, 2, 3 \tag{7}$$

where
l = alternative
k = criterion at level 2; k = 1, 2, …, 7

The scores of the alternatives will give the hierarchy. The best design alternative is the one with the highest score, max S_l.

Conclusions

Increasingly, the product designer's task is made evermore complex due to the legislative pressures and increasing consumer environmental consciousness, in addition to other factors (i.e. technical and economic).

In addressing this situation, the authors proposed the DFE Workbench which includes a strategy module for decision-making at the design stage. Based on AHP, the strategy tool supports the designer in structuring and evaluating different alternatives. It incorporates environmental considerations and constraints stated by legislation and the 'voice of community' in the decision-making process along with economic judgements which can alters the product design decision. The main advantage of the strategy tool from the decision-maker point of view is that he/she is directly involved in the process and the result of the assessment is based on his/her judgement.

In conclusion, the DFE Workbench comprising the DFE Module, the Cost Module and the Strategy Module, represents an integrated solution to the design of environmentally superior products.

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